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Magnetic properties of Chelyabinsk meteorite (15 February 2013) at high temperatures

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Abstract. Magnetic properties of the Chelyabinsk meteorite were studied in a wide temperature range – up to ~ 1300 K. The analysis shows that the meteorite contains ferromagnetic inclusions of both Fe-Ni alloy and pure iron. It has visually been demonstrated that iron inclusions of the Chelyabinsk meteorite experience no $\beta \rightarrow \gamma$ structural phase transformation.

1. Introduction

In several works (e.g., [1–4]) there authors have shown that the Chelyabinsk meteorite contains metallic impurities of the Fe-Ni alloy and iron. That is why studying magnetic properties of this meteorite presents by itself peculiar interest. In the paper [4] with our participation, some fragments of the Chelyabinsk meteorite were investigated. However, we didn't pay sufficient attention to the magnetic properties of meteorite at high temperatures, namely, $T > T_{\text{CFe}}$ (T_{CFe} is the Curie temperature of iron), where the spontaneous magnetization M_s of all the meteorite components is equal to zero. In this article, we examine in detail the magnetic properties of the Chelyabinsk meteorite, with paying special attention to their high temperature behavior. Note that such a task is substantiated by the following circumstance. When analyzing already existent literature data on the magnetic properties of meteorites with inherent ferromagnetic inclusions, we have found no works where their authors investigated the range of temperatures $T > T_{\text{CFe}}$. At the same time, in our opinion, such investigations can provide for obtaining important information on the feasible structural transformations characteristic of the iron and its alloys, which can exist in meteorites as a whole and in the Chelyabinsk meteorite in particular.

2. Experimental details

Magnetic measurements were performed on a specimen of meteorite, as well as on the sample of carbonyl iron (of 99,93% purity), which had a form that resembled that of a ball. The temperature dependence of the magnetization M for the investigated specimens was obtained at a magnetic field strength of $H = 10$ kOe and at a heating rate of 2 K/min. The research was carried out using the equipment (VSM, Lake Shore Cryotronics, USA) of the Collaborative Access Center “Testing Center of Nanotechnology and Advanced Materials” of the Institute of Metal Physics.



3. Results and discussion

The thermo-magnetic analysis is widely used for investigating meteorites; the main aim of its application consists in determining the Curie temperature T_{C1} of a ferromagnetic and/or a ferrimagnetic components.

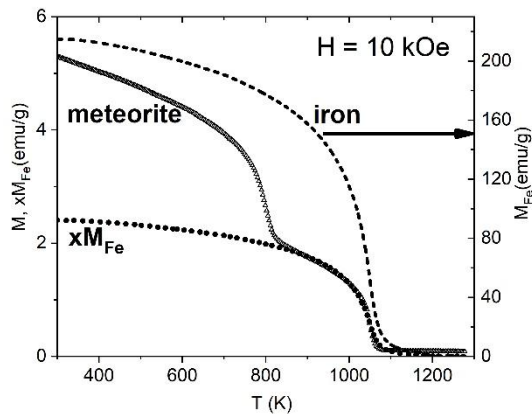


Figure 1. Temperature dependence of magnetization M of investigated samples

The magnitudes T_{C1} corresponded to minimums of the first derivative $\partial M(T)/\partial T$ [5], where T is an absolute temperature.

In the case of a sample of the meteorite, the dependence $M(T)$ has two inflexions (figure 1). Such form of the function $M(T)$ presupposes that the sample consists of at least two ferromagnetic phases. The function $\partial M(T)/\partial T$ (figure 2) has two minimums with corresponding values of the $T_{C1} = 800$ K and $T_{C2} = 1049.6$ K. In the same figure 1, the function $xM_{Fe}(T)$ corresponds to a sample of iron, where $x = \text{const}$ is the weight fraction of Fe in the meteorite. The magnitude $T_{CFe} = 1050.0$ K was determined by one via analogous manner (figure 2). The accuracy of Curie temperature determination was no less than ~ 1 K.

The magnitude $T_{CFe} = 1050$ K is somewhat higher than 1043 K, which is given for iron in numerous handbooks. It is worth mentioning that data presented in handbooks are based on original investigations published in 60-ies of the past century where the Curie temperature was determined in a way different from our study.

In our work, the main attention is given to the second ferromagnetic phase with the magnitude of $T_{C2} = 1049.6$ K.

A first ferromagnetic phase is characterized by $T_{C1} = 800$ K, which corresponds to the temperature of Curie of the taenite – the alloy Fe–Ni with 51% Ni [4].

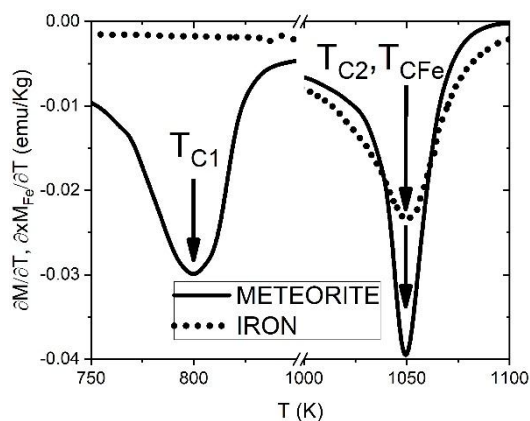


Figure 2. Temperature dependence of first derivative $\partial M(T)/\partial T$ for investigated samples.

The magnitudes of T_{C2} and T_{CFe} are virtually coincident, which points to the presence of a certain quantity of highly pure metallic iron in the sample of meteorite under investigation. Apart from this, the result obtained testifies to that at $T > 800$ K in the sample only one ferromagnetic component is present. All the other components are in the paramagnetic, the diamagnetic, or any other magnetic state with $M_S = 0$ and, at $T > 800$ K, the value of M in the main is determined by the presence of iron. In this case one can suppose that in the range of temperatures $T_{C1} < T < T_{C2}$ for some value of x the dependence $M(T)$ is expected to coincide with the function $xM_{Fe}(T)$. Indeed, it turns out that one can easily sort out the value of x such that in the interval of temperatures $860 \div 1010$ K it would provide for a satisfactory fitting of the function $xM_{Fe}(T)$ to the dependence $M(T)$. An optimum value of x for such fitting amounts to 0.0112 (figure 1). Apparently, this result shows that the main contribution into the magnetization of the sample of our meteorite in the temperature interval specified is from iron. It is expedient to pay attention to that at $T > 1050$ K the value M_S is equal to zero and, with increasing the temperature, the contribution of iron into the integrated magnetization of the sample of meteorite, which contains a vast spectrum of magnetic components, exhibits a decrease.

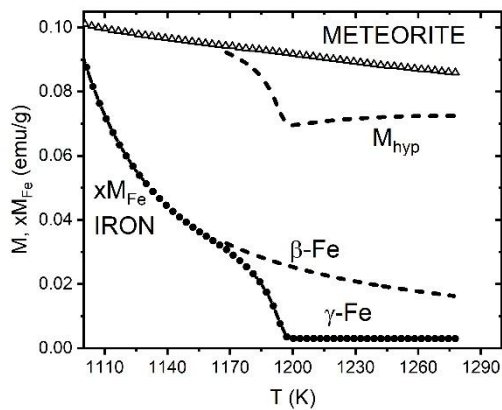


Figure 3. Temperature dependence of magnetization M for investigated samples at $T > T_{CFe}$.

The feasibility of fitting of the function $xM_{Fe}(T)$ to the dependence $M(T)$ of the sample of meteorite is an additional argument for the benefit of the presence of iron in the meteorite. However, we should note that the experimental dependences $xM_{Fe}(T)$ and $M(T)$ are slightly divergent in the vicinity of the Curie temperature. This inconsistency is most noticeable in the functions $\partial M(T)/\partial T$ and $\partial xM_{Fe}(T)/\partial T$ (figure 2). This result can be understood on the basement of most general ideas on the temperature dependence of magnetization of ferro magnetics. In this case it is necessary for one to take into account the fact of that in the case of the sample with a nonzero demagnetization coefficient N the magnetization is connected with the internal field $H_{int} = H - NM\rho$, where ρ is the (weight) density. For a sufficiently large magnitude of $H \geq NM_S\rho$ the measured value of $M(T)$ can be represented in the form $M(T) = xM_S(T) + x\chi_P(T, H_{int})H_{int} + (1-x)\chi_0(T)H$, where χ_P is the susceptibility of the true magnetization of iron, and χ_0 is the mean (average) susceptibility of all the other (chemical) components of the meteorite. If $x\chi_P \gg (1-x)\chi_0$, then the additional magnetization $x\chi_P(T, H_{int})H_{int}$ regulates some difference in the dependence of $M(T)$ measured at a constant H and at various values of N . If $N_1 > N_2$, then for $H = \text{const}$ and $T = \text{const}$ we have a right to assume $M_{N1} < M_{N2}$. At $H = \text{const}$, for homogeneous samples of one and the same ferromagnetic substance, the experimental function $M(N_1, T)$ [its plot] is located lower than does the function $M(N_2, T)$ and the most pronounced difference between these two functions is expected for one to observe in the vicinity of the Curie temperature. In other words, the function $M(T)_{H=\text{const}}$ depends on a sample shape.

Summarizing what was said, one is allowed to suppose that in the meteorite its iron is present in the form of particles with the effective value N that is greater than the value of the demagnetization coefficient typical of the iron sample. It is also worth mentioning that, most likely, the susceptibility χ_0 also exerts effect on the observed divergence of the functions under consideration.

It is well-known that iron experiences the $\beta \rightarrow \gamma$ first-order structural phase transformation at the critical temperature $T_{\beta \rightarrow \gamma} \sim 1180\text{--}1190$ K [6–8]. The transition is accompanied by a considerable change in the magnetization [6, 7].

Upon isothermal conditions, at $T = T_{\beta \rightarrow \gamma}$ the magnitude of magnetization changes drastically. At the same time, in the sample of iron under investigation sharp changes in magnetization are observed in a certain interval of temperatures (figure 3). Such behavior of the function $xM_{\text{Fe}}(T)$ can be connected with the dynamic heating of the sample. Nonetheless, in our experiment the transition terminates at the temperature of ~ 1200 K, which is in agreement with literature data [6 – 8].

One should expect that in the meteorite its iron has also to experience the $\beta \rightarrow \gamma$ phase transformation, which is accompanied by a sharp change in the magnetization. However, the experiment (see figure 3) demonstrates that in the sample of the meteorite under investigation no clear indications of this phenomenon are present, up to the experiment temperature limit of 1280 K.

The obtained data permit to right-well calculate a hypothetical function $M_{\text{hyp}}(T)$ for hypothetical meteorite iron, which undergoes the $\beta \rightarrow \gamma$ transition. It is supposed that $xM_{\text{Fe}}(T)$ is the temperature dependence of magnetization of hypothetical iron in the meteorite. At $T > 1170$ K such function can be represented as $M_{\text{hyp}}(T) = M(T) - x[M_{\beta\text{Fe}}(T) - M_{\text{Fe}}(T)]$, where $xM_{\beta\text{Fe}}$ is the magnetization of the β phase of iron. The values of $xM_{\beta\text{Fe}}$ at $T > 1170$ K were determined with the employment of the Curie–Weiss law, namely, $xM_{\text{Fe}} = xH \cdot C / (T - \Theta)$, at $T < 1170$ K ($xH \cdot C = 3.54$ emu K/g), where C is the Curie constant and Θ is the Weiss constant ($\Theta = 1060$ K).

The obtained function $M_{\text{hyp}}(T)$ (figure 3) clearly shows that the $\beta \rightarrow \gamma$ transition is expected to be sufficiently well recorded within the framework of our experiment. However, this anticipated result is not observed, and we have a right to speak of that meteorite iron is principally different from typically «earthly» iron. This very important (in our opinion) experimental result can be understood using data [9, 10] on the temperature dependence of the susceptibility of iron samples that have a mass of 5–10 mg and a purity of 99.8% [9] and 99.99% [10].

In the works [9, 10], their authors have performed investigations on the great number of iron samples (~ 100) in the wide range of temperatures from 1073 K to 2173 K. In a first series of experiments ([9], iron purity of 99.8%) it was shown that after crystallization, from 100 samples 10 of them did not exhibit structural transformations till the Curie temperature. In a second series of experiments ([10], iron purity of 99.99%) the isomorphous state of iron was characteristic of approximately 50 samples of iron. These experimental results permit one to draw an obvious conclusion on that the less the number of impurities in iron, the lower the possibility of polymorphism realization in the iron.

4. Conclusion

Thus, the absence of the $\beta \rightarrow \gamma$ phase transition in the meteorite iron apparently points to an extremely low level of impurities in it.

We believe that the presented data and their brief analysis point to the necessity of more detailed study of the iron that is contained in the Chelyabinsk meteorite.

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